Defining a consistent strategy to model ground-motion parameters for the GEM-PEER Global GMPEs project

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SUMMARY:
The project entitled Global Ground Motion Prediction Equations is funded by the Global Earthquake Model (GEM) Foundation and has the objective of recommending a harmonized suite of ground motion prediction equations (GMPEs) that can be used at the global and regional scales for seismic hazard analysis and loss estimation studies. As part of this project, Task 1a experts were commissioned to make recommendations on the critical aspects of seismological predictor parameters that are used by predictive model developers to estimate ground motions for different earthquake scenarios. It is hoped that these recommendations would lead to the optimum description of ground-motion models that can be used efficiently for reliable seismic hazard assessment studies.

Keywords: Ground-motion prediction equations (GMPEs), seismic hazard assessment, predictor parameters of GMPEs

1. INTRODUCTION

Ground-motion prediction equations (GMPEs) relate a ground-motion intensity measure to a set of explanatory variables describing the source, wave propagation path and site response. Although these estimator parameters mainly include the magnitude, style-of-faulting and source-to-site distance, there are significant efforts to include additional variables to model the ground-motion behavior in a more realistic way. These variables have different levels of influence on the estimated ground-motion intensity measure. Moreover, each of these variables is affected by different factors that in turn define the level of accuracy of the predictions. This paper is a summary of a report (Task 1a report: Akkar et al., 2011a) prepared under the framework of the "GEM-PEER Global Ground Motion Prediction Equations project. The overall aim of the project is to propose GMPEs for reliable regional and global seismic hazard assessment. Under this objective, Task 1a aimed to identify the significance of each predictor parameter used in the functional forms of GMPEs. To this end, members of Task 1a suggested a set of recommendations for the optimum performance of each major predictor parameter and highlighted the required features of these parameters as well as the predictive models that are believed lead to a consistent seismic hazard assessment. The companion article of Douglas et al. (2012) presents a pre-selection of candidate GMPEs for the same project based on the recommendations made in Task 1a.

2. CONSIDERATION OF GROUND-MOTION INTENSITY MEASURES

The ground-motion intensity measures (IMs) of interest in the predictive models should primarily respond to the needs of the engineering community. Both force-based and displacement-based design and seismic performance assessment codes/guidelines use the pseudo-spectral acceleration (PSA), spectral displacement (SD) as well as peak ground acceleration (PGA) and velocity (PGV) as IMs. The use of these IMs is expected to remain at least for the next decade. Therefore, GMPEs that consider these IMs are of prime importance for hazard assessment. In addition to the above mentioned IMs, GMPEs that consider other ground-motion parameters (e.g., equivalent number of cycles, strong-motion duration, spectral ratios at different damping values, horizontal-to-vertical spectral ratios, Arias intensity and cumulative absolute velocity (CAV)) are also important as they either provide supplementary information to conventional seismic design or more advanced design/risk assessment projects.

The reliability of IMs that are computed from processed records and are used in the derivation of GMPEs needs to be considered, because they affect the ground-motion estimates. The reliable estimation of long-period spectral ordinates is important for base-isolated structures as well as high-rise buildings and long-span bridges. Consistent short-period vertical spectral ordinates become essential for the derivation of horizontal-to-vertical spectral ratios as well as for the design of short-period machinery components mounted on building systems. GMPEs that present a clear documentation on the specific features of the implemented processing procedure as well as describe the usable spectral period range of the processed data are recommended for hazard studies.

The major challenges in data processing schemes that rely on filtering are: (a) minimum interference of filter corner frequencies that result in stable peak ground-motion values and spectral ordinates computed from the processed records, (b) choice of filter cut-off frequencies that result in minimum manipulation in the actual frequency content of the ground motion, and (c) determination of reliable usable spectral period ranges where the influence of processing is minimal. Acausal (zero-phase) filters are the recommended filtering type (e.g., Boore and Akkar, 2003) in order to address the point raised in (a). If time-domain acausal filtering is used, it is necessary to add leading and trailing zero pads at the beginning and end of the recording to accommodate filter transients. Choice of filtering cut-off frequencies can be based on low- and high-frequency behavior of ground motions (e.g., Akkar and Bommer, 2006; Douglas and Boore, 2011). This approach uses theoretical source spectrum behavior and aims at minimum manipulation of the ground-motion data. The usable period band should be as wide as possible to address a large range of engineering applications. There are alternative methods for the computation of usable spectral period range (e.g., Abrahamson and Silva, 1997; Akkar and Bommer, 2006; Douglas and Boore, 2011). The common conclusion of these procedures is that the long-period spectral ordinates are reliable up to a certain fraction of the high-pass filter cut-off and that the low-pass filtering has minimal effects on short-period spectral ordinates. For example, Akkar et al. (2011b) suggest extending the short-period limit of pan-European strong-motion database to at least 0.02 s. The NGA ground-model models use 0.01 s as the shortest period for the calculation of spectral ordinates.

As noted above, recent research tends to extend the usable period range as much as possible to respond to engineering needs. On the other hand, most of the current GMPEs, except for those developed in the NGA project, lack such a wide period band. The NGA models are able to estimate spectral ordinates between 0.01 and 10 s. This limitation can require interpolation of the some of the candidate GMPEs for PSHA for some intermediate periods provided that both ends of the interpolation interval are fixed. When interpolation is required, it can be done either directly on the predicted spectral ordinates or on the regression coefficients. The second alternative (e.g., Bommer et al., 2012) is more flexible, because it offers a wider range of applicability of the interpolated GMPEs (in particular for PSHA studies). Nevertheless caution should be exercised in this alternative if the functional form of the interpolated model is complex and contains a large number of coefficients. Although interpolation of GMPEs for missing spectral ordinates are recommended for hazard studies for reasons explained herein, the extrapolation of GMPEs to both short and long periods is strongly discouraged.

3. CONSIDERATION OF SEISMOTECTONIC REGIONS

Acceptable ground-motion models must consider the differences between the main tectonic regimes. The major tectonic regimes that are the focus of the vast majority of hazard studies are: (a) stable continental regions (SCRs), (b) subduction zones, (c) active shallow crustal regions (ASCRs), (d) volcanic regions, (e) earthquakes with mainly oceanic travel paths (e.g., Portugal) and (f) deep Vrancea-type earthquakes. The models should address the important features of fault mechanisms and source properties that characterize each tectonic regime. Furthermore, models should consider differences in the attenuation of ground-motion amplitudes and in important estimator parameters that can be of particular use for a seismotectonic region. During a hazard study, it is very important to consider the seismotectonic setting for which a model was developed.

There are a number of different regionalizations that describe SCRs. The most widely used classification, based on contrasts in age, tectonic origin and tectonic history, is the one developed by EPRI (Johnston et al., 1994). The EPRI classification was not based on observations of contrasting earthquake source or seismic wave propagation characteristics, although it implied that such contrasts might result from contrasts in tectonic origin and history. The developers of GMPE's for SCRs are now in the process of discovering the degree to which this conjecture is borne out in the actual earthquake source and seismic wave propagation characteristics of these regions. As part of a global effort, the classification needs to be consistent with the other regional hazard studies (e.g., in strain rates). For example, the tectonic regions can be globally separated into shield (cratonic - low deformation with low attenuation) and continental crust (non-cratonic - low deformation but significant attenuation). It is recommended to consider separate GMPEs for the cratonic regions and non-cratonic regions (e.g., Somerville et al., 2009). An attempt towards this suggestion is presented by Delavaud et al. (2012).

There is also a need to set a consistent definition for differentiating between different types of earthquakes associated with a subduction zone (e.g., using depth and focal mechanism). Acceptable ground-motion models should take into consideration the differences existing among, for instance, interface and intraslab earthquakes, and provide separate sets of coefficients for each type of earthquake. This implies that the metadata should maintain accuracy in providing reliable information on earthquake depth, focal mechanism etc. ASCRs are characterized by active tectonics with relatively high strain rates, generally close to plate boundaries, and earthquakes that occur in the upper 20 to 30 km of the crust generally on well-identified mature faults (e.g., California, Italy, Turkey, Greece and Japan). It is often considered that ground motions associated with this type of seismotectonic regime do not show strong regional dependencies, at least for moderate and large earthquakes. The vast majority of published GMPEs were derived for this type of area, partly because of the considerable amount of strong-motion data that are available.

Volcanic earthquakes are unlikely to be larger than about M_w 5.5 (and probably much smaller) and, therefore, the seismic hazard from this type of earthquake is unlikely to be important on a global scale. Although there are almost no ground-motion models specifically estimating the ground-motion amplitudes for earthquakes from volcanic activity, some GMPEs considered earthquake data from volcanic regions (e.g., McVerry et al., 2006; Zhao, 2010). De Natale et al. (1988) proposed a stochastic model for estimating the ground motions of volcanic events in Italy. In the framework of the GEM-PEER project, separate GMPEs may be adopted for regions of volcanic activity in which the historical seismicity is well-documented. Such GMPEs should be able to deal with events of shallow focal depth, from 2 to 5 km. While deep-focus non-subduction earthquakes have occurred or could occur in various seismic prone regions around the world (e.g., Vrancea (Romania) zone, New Hebrides Islands, Baja California, Bucaramanga (Colombia), eastern Anatolia, New Guinea and Pamir Hindu-Kush), there are practically no ground-motion predictive models for such regions. In fact, the only model that exists for the prediction of response spectral ordinates in such a region is the one developed by Sokolov et al. (2008), which is specific to the Vrancea region. In the absence of an adequate number of GMPEs for such regions, it may be suggested to use the GMPEs of intraslab earthquakes for hazard analysis. For offshore seismic hazard studies, a mixture of GMPEs from active and SCRs may be recommended as such regions also lack GMPEs that specifically feature the earthquake source and wave-propagation characteristics of these regions.

4. CONSIDERATION OF MAGNITUDE TYPE AND RANGE

Moment magnitude (M_w) has almost become the standard magnitude scale for developing GMPEs, since it can describe the energy release of an earthquake without suffering from saturation. Although the use of M_w shows a significant increase during the last decade, GMPEs that use M_L (local magnitude) as well as M_s (surface-wave magnitude) still constitute a fairly large fraction in the overall number of available GMPEs. Models that use M_L are generally local GMPEs, whereas many earlier global GMPEs as well as a few local ones have used M_s. Therefore, conversions between magnitude scales are necessary when the magnitude definitions of the GMPEs differ. Although there are quite a few peer-reviewed empirical relations that convert various magnitude scales to a common magnitude definition (e.g., moment magnitude) (Utsu, 2002), they can differ significantly in estimating the target magnitude scale. These relations carry their own uncertainty due to different regression methods adopted in their calculation as well as the different approaches and databases used in the computation of magnitude scales by different seismic agencies.

State-of-the-art seismic-hazard analyses consider error propagation due to the aleatory and epistemic uncertainties inherent in magnitude scaling relationships when GMPEs that use different magnitude definitions have to be converted to a common magnitude format. The error propagation due to magnitude conversion has a larger influence at longer spectral periods and low annual exceedance probabilities in hazard because of their stronger magnitude dependence (Bommer et al., 2005). To avoid such complications, it is suggested to employ GMPEs that adopt M_w as the magnitude scale. If there is a need to use GMPEs of different magnitude definitions, the analyst has to understand the modeling uncertainty stemming from magnitude conversions. Observing differences in spectral ordinate estimates after the application of alternative magnitude conversion relations can be one approach to understand the modeling uncertainty due to magnitude conversion.

Most of the GMPEs are based on data from moderate-to-large earthquakes with magnitudes equal to or greater than 5. Reasons behind this include: (a) existence of a significant number of analog and early digital accelerograms with magnitudes 5 and above, (b) general consensus among the engineering and seismological communities that most structures are not susceptible to damage for magnitude levels less than about 5, and (c) the increased uncertainty in the magnitude determination of small events. However, ground-motion models derived from moderate-to-large earthquakes tend to overestimate the ground motions from small magnitude events and at the lower magnitude limit of their original datasets, which is of particular importance when computing the hazard for regions of low-to-moderate seismicity (e.g., Chiou et al., 2010; Campbell, 2011). Given the current improvements in strong-motion databases, the developers of new GMPEs may want to lower the magnitude limit to M_w 4 or 4.5 so that ground motions near M_w 5 are not overestimated. The GMPEs developed by Chiou et al. (2010) and Atkinson and Boore (2011) can be considered as the early attempts to cover smaller magnitudes in ground-motion modeling.

The upper magnitude limit of applicability of GMPEs generally ranges between 7 and 8 for the most recent models. This magnitude range reflects the maximum magnitudes that can be expected in most seismically-active regions. The recent devastating subduction-interface earthquakes (M_w 8.8 Maule, Chile, and M_w 9.0 Tohoku-oki, Japan) showed that maximum magnitudes could be well above M_w 8 for such earthquakes. These new observations as, well as more refined geological and paleoseismic studies, will eventually push the upper magnitude level above 8 in future GMPEs pending the accumulation of such data in strong-motion databases. In view of the state of practice in the use of current GMPEs, the maximum magnitudes to be considered in SCRs and ASCRs should be in the range of M_w 8. This upper bound should be at least M_w 8.5 for most subduction-interface GMPEs.

5. CONSIDERATION OF SOURCE-TO-SITE DISTANCE MEASURES

The common source-to-site distance measures in GMPEs are R_{epi} (epicentral distance), R_{hyp} (hypocentral distance), R_{rup} (closest distance to rupture surface) and R_{JB} (closest distance to horizontal projection of rupture to the surface, so called Joyner-Boore distance). The latter two distance metrics have become popular as they can address the variation of ground-motion amplitude more appropriately for large events at sites closer to the source. Both R_{rup} and R_{JB} require reliable finite-fault (or rupture model) representations that are generally available for large-magnitude earthquakes or for some specific events that are studied individually. R_{epi} and R_{hyp} are still more accessible in the existing strong-motion databases, because seismic agencies routinely report the seismological parameters required for their calculation (although the depth parameter used for R_{hyp} still contains significant uncertainty in current catalogs). Consequently, there is still a larger number of GMPEs that use either R_{epi} or R_{hyp} (point-source distance measures) Ground-motion models that employ extended-source distance measures (R_{JB} and R_{rup}) are often derived from global strong-motion databases, because such databases are generally developed under the framework of well-funded projects that can recruit experts on database compilation and processing. Many local GMPEs as well as some of the global GMPEs use R_{hyp} or a combination of point- and extended-source distance pairs in their functional forms.

Whenever ground-motion models of different distance metrics are employed in probabilistic seismic hazard analysis (PSHA), the state-of-the- practice is to adjust the differences in distance measures to model consistent earthquake scenarios. Moreover, GMPEs that use extended source distance metrics should be modified properly in order to accurately estimate the hazard due to background seismicity for which earthquake scenarios are treated as point sources. For such distance conversions various proposed relationships may be used (e.g., Johnston et al., 1994; Scherbaum et al., 2004). The major challenge in employing distance conversion relations is the propagation of the error into the estimated ground motions. This uncertainty can lead to larger standard deviations (i.e., increased aleatory variability) in the GMPEs and may significantly increase the hazard (Scherbaum et al., 2005). One approach to avoiding such large uncertainties in hazard calculations is to use hazard codes that are capable of modeling finite-fault sources in such a way that the commonly used distance metrics can be computed and that each GMPE can be used with its original distance definition (Bommer et al., 2010). In a similar fashion, for hazard analysis concerning areal sources for which the earthquake scenarios are defined as points, GMPEs that use R_{JB} or R_{rup} can be employed consistently together with GMPEs that use point-source distance measures, if the hazard software is capable of simulating pseudo-ruptures for each earthquake scenario with random orientations and with dimensions determined from empirical relationships (Bommer et al., 2010). Another reasonably simple method, as implemented by the U.S. Geological Survey, is to use look-up tables of pre-calculated average finite-source distance measures, assuming random azimuth and specific rupture geometries for each point source. As proposed by Bommer and Akkar (2012), a more pragmatic solution for using consistent distance metrics in hazard calculations is to develop GMPEs in pairs; one that uses an extended-source distance metric for PSHA applications to finite-fault sources and another that is based on either R_{epi} or R_{hyp} to properly consider the contribution of areal sources. The discussed methodologies in this paragraph are recommended for computing reliable hazard results while adjusting the ground-motion estimations of GMPEs that use different distance measures.

6. CONSIDERATION OF STYLE-OF-FAULTING

The consideration of style-of-faulting (SoF) as a predictive parameter in GMPEs is now common. As is often the case for empirical models, there can be strong trade-offs between the SoF factor and other predictive parameters such as source depth. Reliable source-depth information is important for identifying the rupture mechanisms as well as different tectonic regimes for subduction zones. Depth and fault mechanism, or centroid moment tensor (CMT) information, provides a good way to distinguish crustal, interface and intraslab subduction earthquakes. The classification schemes used for mapping the earthquakes into different fault mechanisms and the database distribution also affect the estimated ground-motion amplitudes for different types of faulting. Using the plunge of the P, T and B axes seems to be a reliable way of classifying different styles-of-faulting, although rake angle schemes yield consistent SoF classifications for many cases. Thus, use of the plunge of the P, T and B axes should be verified with the rake angle intervals as implemented by Boore and Atkinson (2008) in order to reduce the number of unclassified earthquakes in terms of SoF.

Currently most of the global GMPEs and a few local ones address SoF. The ground-motion models that include the SoF predictor parameters should be preferred in PSHA as long as they address correlations with other parameters that can also explain the observations and are proven to be efficient and accurate for the considered seismic region. Bommer et al. (2003) proposed a scheme to incorporate SoF into GMPEs that either consider only one fault mechanism or are independent of fault mechanisms. Unless there are compelling reasons for using such adjusted GMPEs in the hazard analysis, the use of methodologies that externally adjust the estimated ground-motion amplitudes for SoF effects should be avoided, since such manipulations would increase the uncertainty in the estimated ground motions.

7. CONSIDERATION OF NEAR-FAULT EFFECTS (DIRECTIVITY / DIRECTIONALITY)

To accurately characterize near-fault ground motions, directivity and directionality effects should be taken into account. Directivity effects generally increase spectral accelerations for periods longer than approximately 0.5 s at locations where the rupture has propagated primarily towards the site of interest. At locations where the rupture has propagated primarily away from the site, spectral accelerations generally decrease. Forward-directivity effects are manifested in the presence of a short-duration velocity pulse, which is not modeled by most GMPEs. The directivity effect depends upon rupture direction and additional predictor parameters are needed to account for this effect. Most directivity models use a description of the amount of rupture that has ruptured towards the site of interest either as an absolute distance or a fraction of the total length of rupture. Directivity models require the specification of hypocenter location and the size and orientation of the rupture plane as well as the dependence of directivity effects on fault mechanism.

The directivity model developed by Somerville et al. (1997) provides separate predictions of the strike-normal and strike-parallel components of motion, and was later modified by Abrahamson (2000) for strike-slip earthquakes. These models are currently widely used for hazard calculations because they use simple parameters that are easy to implement. The Somerville et al. (1997) model indicates a strong dependence of the ratio of strike-normal to average horizontal motions on magnitude and rupture length. The ratio of strike-normal to average horizontal motions is found to be period-dependent and becomes significant for periods greater than 0.6 s. The model by Somerville et al. (1997) also includes systematic variations of duration in near-fault ground motions due to directivity.

Simple time-domain pulses can represent near-fault ground motions containing forward rupture directivity. Various studies developed equations relating the period of the pulse to the earthquake magnitude and the effective velocity of the pulse to the earthquake magnitude and distance (e.g., Somerville, 2003). Although considerable differences exist between the predictions by different models, all of the correlations show a similar trend of pulse period increasing with earthquake magnitude. For large surface faulting earthquakes (e.g., the M_w 7.6 Chi-Chi earthquake), the value of the pulse period may also be affected by the large permanent displacements accompanying the fault rupture.

There are also more complicated models for directivity, such as the one developed by Rowshandel (2010) within the NGA project, or the ones that are currently studied within the framework of the NGA-West2 project. The model proposed by Rowshandel (2010) is capable of handling every type of rupture direction, because they generalize the directivity predictors of Somerville et al. (1997) by applying a surface integral over the fault for every receiver location. Based both on analysis of ground motion simulations and the database of recorded ground motions developed for the NGA project, Spudich and Chiou (2008) developed a new physically-based directivity model using isochrone theory. Their model provides an improved characterization of directivity over earlier models. However, the Spudich-Chiou model is most applicable to the NGA GMPEs and would likely be difficult to apply to other models. The Spudich-Chiou directivity model currently does not address differences between strike-normal and strike-parallel components. Under these discussions, the Somerville et al. (1997) and Abrahamson (2000) studies seem to constitute the most suitable and practical models, while considering near-fault effects on ground-motion amplitudes, until the other mentioned models have been implemented widely to assess their level of practicality in a state-of-the-art PSHA.

Most GMPEs estimate the average ("geometric mean") of the response spectra of two horizontal components. In some cases it may be of greater interest to know the maximum spectral value, over all possible orientations, at a given period. Various models are proposed for making such a "maximum direction" prediction (e.g., Boore, 2010). Loosely speaking, the maximum-direction spectral value will be about 1.2 times the geometric mean value at short periods and 1.3 times the geometric mean value at long periods.

8. CONSIDERATION OF OTHER IMPORTANT PARAMETERS: BASIN EFFECTS, DEPTH TO TOP-OF-RUPTURE, $Z_{1.0}$, $Z_{2.5}$, NONLINEAR SITE EFFECTS AND V_{S30}-KAPPA CORRELATIONS

Many additional predictor parameters are important in the reliable estimation of ground motion and their consideration in GMPEs has proven to be useful (see discussions by NGA model developers). For instance, parameters such as Z_{TOR} (depth to top-of-rupture), $Z_{1.0}$ and $Z_{2.5}$ (depth from the ground surface at which shear-wave velocity attains values of 1.0 km/s and 2.5 km/s, respectively) are important for forward calculations, in particular for site-specific hazard analysis. The parameter R_x, the shortest horizontal distance to the top edge of rupture measured perpendicular to the strike (site coordinate), has also an important role when considering hanging-wall effects. However, such information is still limited in the metadata of strong-motion databases. Thus, consideration of such parameters in ground-motion models may still not be recommended unless the model developer assures their reliability. Kaklamanos et al. (2011) propose default values for fault dips, Z_{TOR} and other parameters used in the NGA models when they are unknown. However, care should be taken in evaluating how error propagates when considering these "default" values.

Nonlinear site effects are currently estimated by using the average shear-wave velocity in the upper 30 m of the soil profile (V_{S30}). Measured V_{S30} values are still rare in many strong-motion databases and many ground-motion equations still consider generic soil classes to model site effects. The average V_{S30} and kappa (high-frequency filter commonly considered to be related to near-surface attenuation) on rock can significantly affect short-period response spectral ordinates. GMPEs developed for different parts of the world have used different rock definitions and consequently require calibration to a specific rock classification. This is reasonably straightforward for models that treat V_{S30} as a variable. V_{S30} and kappa are generally considered to be correlated (e.g., van Houtte et al., 2011). Therefore, a coupled V_{S30}-kappa correlation, despite large uncertainties, can be used to calibrate GMPEs for a specific rock definition (Van Houtte et al., 2011). In the context of this project such relationships are encouraged to provide guidance in hazard analysis to describe rock conditions in different parts of the world.

9. CONSIDERATION OF DISPERSION ABOUT MEDIAN

The idealizations imposed in the ground-motion models result in differences between the observed and estimated ground-motion IMs. This dispersion is described by the standard deviation (sigma) associated with the GMPE. Sigma is usually interpreted as describing the aleatory variability of ground motion, but it can also convey information on the epistemic (modeling) uncertainty due to differences in functional forms. The value of sigma has a significant impact on the seismic hazard analysis, in particular, at low annual exceedance rates (Bommer and Abrahamson, 2006).

The quality, selection and record processing of the strong-motion data can affect the accuracy of predicted ground-motion parameter that in turn can result in high values of sigma (Strasser et al., 2009). The uneven distribution of the database can also increase the value of sigma. The reliability of metadata information of the strong-motion database will contribute to sigma as well. For example Abrahamson and Silva (2008) indicated that consideration of measurement errors in magnitude and depth-to-top of rupture can reduce the inter-event variability at long periods. In fact, recent GMPEs consider the magnitude effect on the dispersion about median estimations, because a decrease in magnitude seems to inflate sigma due to the larger errors involved in the magnitude, location and depth of smaller events (e.g., Abrahamson and Silva, 2008; Chiou and Youngs, 2008). There are counter observations finding no significant evidence for the dependence of sigma on magnitude, which may be related to the specific features of the database used in developing the GMPE. Other than magnitude, some studies find the dependence of sigma on distance and soil behavior. Increased nonlinear behavior of soil deposits also leads to a reduction in intra-event variability. While some estimator parameters contribute to the level of sigma as summarized above, Boore and Atkinson (2008) indicated that inclusion of SoF does not have a significant impact on sigma. However, disregarding SoF effect on sigma can be disadvantageous for site-specific hazard studies that are dominated by a specific rupture type. Inclusion of additional predictor variables in the GMPEs can reduce the sigma, but this effort requires well-constrained metadata information. Sigma can also be controlled by studying the behavior of its individual components of variability associated with a single event or a single station (e.g., Rodriguez-Marek et al., 2011). Such studies can be of use for site-specific hazard studies.

A proper consideration of the influence of the previously mentioned predictor parameters (and similar ones) in functional forms as well as the use of high-quality strong-motion databases and the use of efficient regression techniques (e.g., maximum-likelihood methods) in the development of GMPEs that address the variation of different components of sigma are recommended.

10. CONSIDERATION OF SIMULATION-BASED GMPEs

The earthquake source involves a complex rupture process on a fault, seismic waves arrive at the site by propagation through a complex waveguide, and complex local geology can have an important influence on the recorded ground motions. Strong-motion simulation methods have the advantage over empirical methods by allowing the incorporation of information about earthquake source, seismic wave propagation, and local site characteristics that are specific to the region and to a specific site location. Modern seismic hazard analysis for regions of sparse data (e.g., SCRs or ASCRs with limited number of strong-motion recordings) generally requires GMPEs that are based on ground-motion simulations, because the available observational data in such regions are insufficient to properly constrain the parameters in a GMPE. Even in tectonically active regions, the ground motions that dominate seismic hazards at return periods used in seismic design are often for large magnitudes and close distances; there are few records in the strong-motion databases at such magnitudes and distances, although this limitation is being reduced. Synthetic accelerograms can also supplement the strong-motion database where the data distribution is poorly constrained in terms of independent predictor parameters such as magnitude, distance, SoF etc. Stochastic (either point- or finite-source) (e.g., Boore, 2003; Motazedian and Atkinson, 2005) and broadband simulation methods (e.g., Graves and Pitarka, 2010; Somerville et al., 2009) can be used to develop GMPEs for determining the deterministic and probabilistic estimates of design ground motion. In addition to recent simulation-based GMPEs, the hybrid empirical method has become popular (e.g., Campbell, 2003). This approach estimates ground motions in regions of limited data (target regions) by calibrating reliable GMPEs from regions of abundant data (host regions).

All of these methods depend on a detailed parameterization where the assessment of simulated ground motions and related uncertainties may be difficult for regions that are poorly covered by seismological networks and studies. The ideal target regions are, therefore, those with a rate of seismicity such that the path and site properties can be determined from small magnitude earthquakes. In PSHA implementation for regions that lack strong-motion data, GMPEs derived from point-source and extended-source stochastic simulations (that properly address epistemic uncertainty) are appealing as these methods are easy to apply. The stochastic methods can also be used efficiently in hybrid empirical and composite techniques, which can also be considered for PSHA studies of regions lacking GMPEs due to sparse strong-motion data. The consistent use of stochastic methods in PSHA depends on their suitability for the region under consideration. Their validity is suggested to be checked with few available regional strong-motion records, assuming that such data exists. Provided that adequate knowledge of the seismological parameters is available, the hybrid techniques to simulate broadband ground motions can be used in site-specific PSHA studies. Such methods can also account for the epistemic uncertainty and are capable of addressing the propagation of uncertainties on the simulated ground motion parameters.

11. CONCLUSION

The recommendations made throughout the paper are believed to be important for consistent modeling of ground motions as well as for increased performance of each predictor parameter. These recommendations constitute one of the building blocks for stable and reliable seismic hazard assessment at regional and global scales. A comprehensive list of references that cannot be cited due to space limitations in this paper can be found in Akkar et al. (2011a). The list of recommended GMPEs that generally meet the criteria presented in this paper are available in Douglas et al. (2012).

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